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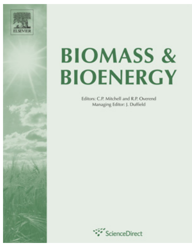

Life cycle assessment of a corn stover torrefaction plant integrated with a corn ethanol plant and a coal fired power plant

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ABSTRACT

A life cycle assessment (LCA) study was conducted to understand and assess potential greenhouse gas (GHG) emissions reduction benefits of a biomass torrefaction business integrated with other industrial businesses for the use of the excess heat from the torrefaction off-gas volatiles and biocoal. A torrefaction plant processing 30.3 Mg h^{-1} of corn stover at 17% wet basis (w.b.) moisture content was modeled. The torrefaction plant produced 136,078 Mg y^{-1} of biocoal at 1.1% w.b. moisture content and 28.1 MW of excess heat energy in the torrefaction off-gas volatiles. At the torrefaction plant gate, the life-cycle GHG emission for the production of biocoal (including corn stover logistics emissions) is 11.35 g MJ^{-1} carbon dioxide equivalent (dry basis) (i.e., 229.5 kg Mg^{-1} carbon dioxide equivalent of biocoal at 1.1% w.b. moisture content). The excess heat from the torrefaction plant met 42.8% of the process steam needs of a U.S. Midwest dry-grind corn ethanol plant producing 0.38 hm^3 y^{-1} of denatured ethanol, which results in about 40% reduction in life-cycle GHG emissions for corn ethanol compared to gasoline. Co-firing 10%, 20%, and 30% (energy basis) of biocoal at a coal-fired power plant reduced the life-cycle GHG emissions of electricity generated by 8.5%, 17.0%, and 25.6%, respectively, compared to 100% coal-fired electricity. A sensitivity analysis showed that adding a combined heat and power (CHP) system at the torrefaction plant to meet 100% electricity demand of the torrefaction plant (2.5 MW) could further reduce the GHG emissions for biocoal, corn ethanol, and co-fired electricity.

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1. Introduction

Using biomass feedstocks to replace fossil fuel sources has the potential to reduce greenhouse gas (GHG) emissions. For thermo-chemical conversion of biomass feedstocks, upgrading of biomass feedstocks by the torrefaction process is proven to be advantageous [1–3]. Torrefaction is a thermo-chemical treatment (roasting) of biomass at 200–320 °C. It is carried out under atmospheric conditions and in the absence of oxygen. During the process, the water contained in the biomass as well as superfluous volatiles are removed, and the

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biopolymers (cellulose, hemicellulose and lignin) partly decompose giving off various types of volatiles (i.e., torrefaction off-gas volatiles). Heat to drive the torrefaction process is contributed by the biomass being processed (i.e., heat from combustion of torrefaction off-gas volatiles). The final product is the remaining solid, dry, blackened material which is referred to as “torrefied biomass” or “biocoal”. Torrefied biomass is a homogeneous material that is brittle, hydrophobic, easy to grind, easy to densify, and has an energy density similar to coal [3–7]. With its high energy density and resistance to degradation and absorption of water, torrefied biomass should be quite compatible with the logistics system serving coal in the U.S. and around the world. The volatile gases driven off during torrefaction may be combusted for other beneficial uses beyond providing the necessary heat to sustain the torrefaction reaction and dry the biomass entering the torrefaction chamber. In many cases, 30% of the mass is driven off while only 10% of the heat energy from the raw biomass is lost in the torrefaction process [4].

Several commercial developments on torrefaction systems such as Agri-Tech (North Carolina, USA), ECN (Netherlands), Thermya (France), Topell Energy (Netherlands), and Torrsys (Bepex International LLC, Minnesota, USA) are currently in their early phase of commercial market introduction [2]. Modeling of mass and energy balances along with economic analysis for production scale biomass torrefaction systems (25–28 Mg h^{-1} of biocoal production) has been reported in the literature [4,8]. To the authors' knowledge, life-cycle GHG emission analysis on biomass torrefaction systems has not been conducted to date.

The overall goal of this research is to understand and assess the potential GHG emissions reduction benefits of a biomass torrefaction business when it is integrated with other industrial businesses for the use of the excess heat from the torrefaction off-gas volatiles and biocoal. The specific objectives of this research are 1) to determine life-cycle GHG emission for the production of biocoal from corn stover, 2) to determine potential reduction in life-cycle GHG emissions for corn ethanol due to the use of excess heat from the torrefaction off-gas volatiles, and 3) to determine potential reduction in life-cycle GHG emission for coal-electricity due to co-firing of biocoal at a coal-fired power plant.

2. Life cycle assessment (LCA) methodology

2.1. Goal and scope definition

The LCA study was performed for the following three scenarios.

Scenario 1 is to estimate life-cycle GHG emissions for production of biocoal from corn stover. The functional unit for LCA is production of one Mg of biocoal at a stationary torrefaction plant. The LCA boundary includes corn stover supply logistics, torrefaction process (corn stover grinding, drying, and torrefaction reaction), torrefaction off-gas volatiles combustion, densification (roll press briquetting) and cooling of biocoal, natural gas input, and grid electricity import. Although several biomass torrefaction systems/concepts have been proposed in the literature, the corn stover torrefaction system developed by Bepex International [9] is used for our analysis. Due to the lack of data on commercial scale performance of the biomass torrefaction plants and to avoid potential errors in the LCA analysis, we did not generalize the torrefaction process based on different proposed biomass torrefaction methods reported in the literature. GHG emission for the torrefaction plant capital is assumed to be negligible considering the functional unit and economic life of the plant.

Scenario 2 is to estimate life-cycle GHG emissions reduction for corn ethanol compared to gasoline due to co-location of a corn stover torrefaction facility with a U.S. Midwest natural gas-fueled dry-grind corn ethanol plant (Fig. 1). The torrefaction facility will supply steam to the ethanol plant. The ethanol plant will supply carbon dioxide (inert gas) to the torrefaction process. The functional unit for LCA is production and use (combustion) of one MJ of denatured ethanol containing 2% (by volume) gasoline denaturant. The life-cycle GHG emission (including production, transport, and combustion) of 92.3 g MJ^{-1} carbon dioxide equivalent of gasoline, and lower heating value (LHV) of 32.6 MJ dm^{-3} are assumed for the conventional gasoline [10]. The LCA boundary for the “base case” natural gas-fueled dry-grind corn ethanol includes corn production and transport, ethanol production, natural gas input, grid electricity import, co-product processing and distribution for animal feed, denaturant (gasoline) contribution (production, transport, and combustion), ethanol distribution, combustion of ethanol (anhydrous), and farm equipment and biorefinery capital emissions.

When the corn stover torrefaction facility is co-located with the corn ethanol plant, the “base case” LCA system boundary is added with steam from the torrefaction plant utilized by the ethanol plant, and CO_2 gas from the ethanol plant sent to the torrefaction plant. The amount of natural gas input to the ethanol plant depends on the amount of steam sent from the torrefaction plant. It is noted that the ethanol plant imports electricity from the grid for all cases analyzed in this study. Credit is assigned for avoided life-cycle GHG emissions for products displaced by ethanol co-product sold as animal feed. In addition, this study does not include estimates of the GHG emissions related to land use change effects of corn ethanol. An LHV of denatured ethanol (containing 2.0% by volume conventional gasoline denaturant) of 21.5 MJ dm^{-3} is used for the analysis [11].

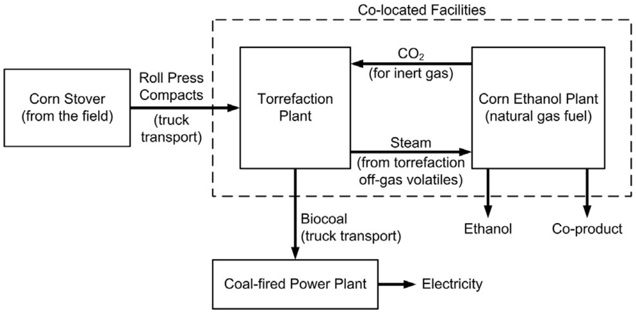

Fig. 1 – Schematic showing the integration of a corn stover torrefaction plant with a corn ethanol plant and a coal-fired power plant.

Scenario 3 is to estimate life-cycle GHG emissions reductions for electricity generated from the coal-fired power plant due to co-firing of biocoal. The functional unit for LCA is production and use (at user wall outlet) of one kWh of electricity. The LCA boundary includes coal production and transport to the power plant, biocoal production and transport to the power plant, power plant operation, electricity export to the grid, and electricity use at a user wall outlet. Three biocoal co-firing percentages of 10%, 20%, and 30% (energy basis) are considered for this study. We have limited the biocoal co-firing percentage to 30% (energy basis) based on Bepex International [9] who successfully co-fired 10%–30% (energy basis) of corn stover biocoal with coal without severe boiler issues such as ash-fouling.

A sensitivity analysis was conducted to study the effect of a combined heat and power (CHP) system installed at the torrefaction plant to meet 100% electricity demand of the torrefaction plant on the GHG emissions for biocoal, corn ethanol, and co-fired electricity.

Credit for the use of biocoal ash is not included in this study because potential application of biocoal ash has not been reported in the literature. Use of biocoal at the coal-fired power plant could reduce sulfur oxides (SO_x), nitrogen oxides (NO_x), and mercury (Hg) emissions; however, emissions other than GHG emissions [carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)] are excluded from this LCA study.

For the grid electricity, the at-the-plug life-cycle GHG emission for the U.S. Midwest average grid electricity of 910 g kWh^{-1} carbon dioxide equivalent is used in our analysis [11,12]. To estimate GHG emissions from the natural gas use, the life-cycle GHG emission (including production, transport, and combustion) for natural gas of 66.3 g MJ^{-1} carbon dioxide equivalent of natural gas is assumed [10].

2.2. *Inventory analysis*

2.2.1. *Corn stover supply logistics*

The “field-to-facility” corn stover logistics system proposed by Morey et al. [13] was modeled to deliver corn stover to the torrefaction plant year around. Table 1 provides energy consumption and GHG emissions for various logistical operations. Detailed calculation procedures for the logistics system can be found in Ref. [13]. Some of the key parameters/assumptions of Morey et al. [13] corn stover logistics system are given below.

The logistics system includes collection (i.e., stalk shredding, raking, and baling) and transport of round net-wrapped bales [1.8 m diameter × 1.5 m width; 4 wraps of net-wrap per bale] of corn stover to local storages within 3.2 km of the field during the fall harvest period. This stage is followed by processing at the local storage sites throughout the year using mobile units, which convert the bales to bulk material by tub-grinding with 76.2 mm screen opening size and roll-press compaction to 240 kg m^{-3} to achieve 22.7 Mg loads for truck delivery to an end user (i.e., torrefaction plant) within a 48 km radius.

Morey et al. [13] assume that 70% corn stover is removed per unit land area with collection every other year that corn is grown resulting in an average removal rate of 35% per year. This leads to more efficient, less costly collection with less compaction than harvesting 35% of the stover each year. Corn stover removal rate is 7.4 Mg ha^{-1} of dry matter [8.7 Mg ha^{-1} of corn stover at 15% wet basis (w.b.) moisture content]. Morey et al. [13] exclude soil organic carbon (SOC) changes from stover removal because the system is based on sustainable removal rates of an average of 35% per year.

Nutrient replacement for the material removed from the field is considered. Nitrogen, phosphorus, and potassium fertilizers are applied at a rate of 7.4, 2.9, and 12.7 kg Mg^{-1} of corn stover dry matter, respectively [17]. N_2O emission from the applied nitrogen (i.e., 1.325% of nitrogen in the fertilizer is emitted as N_2O), and N_2O credit due to corn stover removal (i.e., N_2O avoided per unit of nitrogen in corn stover removed is 1.25% dry basis) are included [10,13]. The nitrogen content of corn stover is 0.69% dry basis [16].

Morey et al. [13] used tub-grinding and roll-press compaction energy obtained from literature sources. We have updated these two energy data with measured values. Tub-grinding energy of 226 MJ Mg^{-1} [14], and roll-press compaction energy of 226 MJ Mg^{-1} [15] are derived for a capacity of 22.7 Mg h^{-1} of corn stover (15% w.b. moisture content) processing. It is assumed the tub-grinder is powered by a diesel engine of 403 kW. Similarly, the roll-press compactor is assumed to be powered by a diesel engine of 403 kW.

2.2.2. *Torrefaction plant*

In this study, the corn stover torrefaction system developed by Bepex International LLC, Minneapolis, MN is considered. The

Table 1 – Life-cycle fossil energy consumption and life-cycle greenhouse gas (GHG) emissions (carbon dioxide equivalents) for corn stover supply logistics.

Logistics operation	Energy consumption (MJ Mg^{-1} of corn stover dry matter)[a]	GHG emission (g MJ^{-1} of corn stover dry matter)[b]
Nutrient replacement	485.58	2.18
Collection/transport to local storage	231.64	0.92
Local storage loss of 5% of corn stover dry matter[c]	35.86	0.16
Tub-grinding/roll-press compaction	661.14	3.02
Truck transport of compacted corn stover	73.37	0.34
Total	1487.59	6.61

[a] Energy consumption for tub-grinding and roll-press compaction processes are updated based on Kaliyan et al. [14,15], and the rest of the energy consumption data are from Morey et al. [13].

[b] Lower heating value (LHV) of corn stover is taken to be 16.7 MJ kg^{-1} of dry matter [16].

[c] Morey et al. [13] assume an average dry matter loss of 5% during storage. The energy or GHG emission due to storage loss is equal to the sum of 5% of the corresponding values for nutrient replacement, and collection/transport to local storage.

torrefaction process data given in this section were obtained from Bepex International [9] unless other sources cited. The torrefaction plant is assumed to process corn stover at a feed rate of 30.3 Mg h^{-1} at 17% w.b. moisture content. The plant operates 8161 h y^{-1} (i.e., 93.2% operational uptime at the plant) and produces 136,078 Mg y^{-1} of biocoal at 1.1% w.b. moisture content.

According to Bepex International [9], the corn stover torrefaction process involves grinding corn stover (17% w.b. moisture content) feedstock in a hammer mill with 6.35 mm screen opening size before feeding it into the torrefaction reactor where corn stover is converted into torrefaction off-gas volatiles and torrefied material (biocoal). About 0.44 MW of natural gas (52.2 MJ Mg^{-1} of corn stover) is mixed to assist the combustion of torrefaction off-gas volatiles. Energy from the torrefaction off-gas volatiles is used to meet the torrefaction process heat energy demand (i.e., drying from 17% moisture content to 0% moisture content plus heating to 250–300 °C for a torrefaction reaction time of 1–5 min). The hot torrefied material is compressed in a roll press briquetter to a bulk density of 640 kg m^{-3}. Finally, the biocoal briquettes are cooled from 300 to 100 °C by quenching with sprayed water followed by fan cooling from 100 to 25 °C. Furthermore, the torrefaction process requires 1.209 Mg h^{-1} of CO_2 gas as inert gas, which may be obtained from the combustion of torrefaction off-gas volatiles at the torrefaction plant itself or from a nearby corn ethanol plant when the torrefaction plant is co-located with the corn ethanol plant. Energy and GHG emissions associated with the use of inert gas are assumed to be negligible.

The energy balance for the corn stover torrefaction process [9] shows that about 34.4% of corn stover dry matter transforms into torrefaction off-gas volatiles. The torrefaction off-gas volatiles contain 22.5% of feedstock energy content. Production rate of torrefaction off-gas volatiles (dry matter basis) is 8.6 Mg h^{-1} and its heating value is 11,705 kJ kg^{-1} of volatiles (dry matter basis). After meeting the heat demand of the torrefaction process, the torrefaction plant produces 28.1 MW of excess heat in the torrefaction off-gas volatiles. About 65.6% corn stover dry matter is converted into biocoal, which contains about 74.5% of feedstock energy. The production rate of biocoal dry matter is 16.5 Mg h^{-1}. The heating value of biocoal is 20,225 kJ kg^{-1} of biocoal at 1.1% w.b. moisture content (20,450 kJ kg^{-1} of biocoal dry matter).

The energy consumption for grinding corn stover feedstock in a hammer mill with 6.35 mm screen opening size is estimated at 41.67 kWh Mg^{-1} of corn stover based on data from Balk [18] and Bitra et al. [19]. The torrefaction plant modeled in this study used a continuous torrefaction process, but the specific design of the torrefaction reactor was not reported by Bepex International [9]. So, the torrefaction reactor parasitic energy consumption of 62 kWh Mg^{-1} of biocoal dry matter (33.76 kWh Mg^{-1} of corn stover) is derived from Bergman et al. [4]. The GHG emissions from corn stover feedstock grinding, torrefaction reactor parasitic energy consumption, and natural gas use for the combustion of torrefaction off-gas volatiles are allocated between torrefaction off-gas volatiles and biocoal based on the percentage of corn stover dry matter contained in them (i.e., allocation based on a dry mass basis) (Table 2). It is noted that we compared mass, energy, and market value based GHG emission allocation methods to allocate the GHG emissions (for the torrefaction process) between the torrefaction off-gas volatiles and biocoal, and found that the differences among these allocation methods were small. We chose a mass based allocation for this LCA study to

Table 2 – Energy and greenhouse gas (GHG) emissions (carbon dioxide equivalents) for torrefaction plant processing 30.3 Mg h^{-1} of corn stover at 17% wet basis moisture content.

Emission source	Energy use per Mg of corn stover processed	GHG emission
Torrefaction plant operation		
Grinding corn stover (6.35 mm screen in hammer mill)	41.67 kWh	1148.43 kg h^{-1}
Torrefaction reactor parasitic energy	33.76 kWh	930.44 kg h^{-1}
Natural gas use for combustion of torrefaction off-gas volatiles	52.22 MJ	104.86 kg h^{-1}
Densification (roll press briquetting) of biocoal	4.84 kWh	133.32 kg h^{-1}
Cooling of biocoal	0.69 kWh	19.09 kg h^{-1}
GHG emissions		
GHG emission to produce torrefaction off-gas volatiles[a]	–	751.19 kg h^{-1}
GHG emission to produce biocoal[b]	–	1584.94 kg h^{-1}
GHG emission for torrefaction off-gas volatiles, torrefaction contribution[c]	–	7.42 g MJ^{-1} of volatiles (dry basis)
GHG emission for biocoal, torrefaction contribution[d]	–	4.74 g MJ^{-1} of biocoal dry matter

Note: Total electricity demand of torrefaction plant = 41.67 + 33.76 + 4.84 + 0.69 = 80.95 kWh Mg^{-1} of corn stover. Since the torrefaction plant processes 30.3 Mg h^{-1} of corn stover, the electricity demand is 2.5 MW.

[a] GHG emission for torrefaction off-gas volatiles = 0.344 × (GHG emissions for grinding + torrefaction reactor parasitic energy + natural gas use). Since 34.4% of corn stover dry matter is converted into torrefaction off-gas volatiles, 34.4% of the GHG emissions from grinding, torrefaction reactor parasitic energy, and natural gas use are allocated to torrefaction off-gas volatiles.

[b] GHG emission for biocoal = [0.656 × (GHG emissions for grinding + torrefaction reactor parasitic energy + natural gas use)] + (GHG emissions for densification + cooling of biocoal). Since 65.6% of corn stover dry matter is converted into biocoal, 65.6% of the GHG emissions from grinding, torrefaction reactor parasitic energy, and natural gas use are allocated to biocoal.

[c] Production rate of torrefaction off-gas volatiles is 8.6 Mg h^{-1} (dry matter basis) and its heating value is 11,705 kJ kg^{-1} of volatiles (dry matter basis) [9].

[d] Production rate of biocoal dry matter is 16.5 Mg h^{-1} and its heating value is 20,450 kJ kg^{-1} of biocoal dry matter [9].

allocate the GHG emissions between the torrefaction off-gas volatiles and biocoal.

The energy required for roll press briquetting of torrefied corn stover to a bulk density of 640 kg m^{-3} is 8.9 kWh Mg^{-1} of biocoal dry matter (4.84 kWh Mg^{-1} of corn stover) [9]. Binders (additives) may be required for roll press briquetting of corn stover biocoal [9], but we did not include the binders in our LCA analysis. The amount of water required for cooling is estimated based on an energy balance: [(mass of biocoal × specific heat of biocoal × change in temperature) = (mass of cooling water evaporated × heat of vaporization of water)]. Specific heat of biocoal is assumed to be 2 kJ kg^{-1} K^{-1} [8]. The heat of vaporization of water is 2257 kJ kg^{-1} of water. Thus, the amount of cooling water required is 177.2 dm^3 Mg^{-1} of biocoal dry matter. Based on Energy® Wise [20], water pumping energy (deep well) requirement is 1.5 kWh per 3785.4 dm^3 of water. So, the water pumping energy is estimated at 0.07 kWh Mg^{-1} of biocoal dry matter. Fan cooling energy is estimated based on the specification for a horizontal pellet cooler given by PiLCO [21]. To cool 16.5 Mg h^{-1} of biocoal dry matter, a horizontal cooler requires 8 fans with each fan operated with a 2.24 kW motor. Assuming a fan motor efficiency of 0.90, the fan cooling electricity consumption is estimated at 1.20 kWh Mg^{-1} of biocoal dry matter. Thus, the total electricity consumption for pumping cooling water and fan cooling is 1.27 kWh Mg^{-1} of biocoal dry matter (0.69 kWh Mg^{-1} of corn stover).

Table 2 summarizes the energy and GHG emissions inventory data for corn stover torrefaction process.

2.2.3. *Corn ethanol plant*

Co-location of a corn stover torrefaction plant with a capacity of 136,078 Mg y^{-1} of biocoal (1.1% w.b. moisture content) with a recently constructed U.S. Midwest natural gas-fueled dry-grind corn ethanol plant with a capacity of 0.38 hm^3 y^{-1} of denatured ethanol is modeled. The ethanol process data reported in this section were obtained from the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) Aspen Plus model of the dry-grind ethanol process [22–24] unless other sources cited. The ethanol plant operates 330 d y^{-1} and 24 h d^{-1}. The denatured ethanol production rate is 47,777 dm^3 h^{-1}. The denatured ethanol yield of 0.412 dm^3 kg^{-1} of corn is used for the analysis [11]. The ethanol process produces about 2.85 kg of CO$_2$ gas from fermentation per 3.785 dm^3 of anhydrous ethanol. A 0.38 hm^3 y^{-1} of corn ethanol (denatured) plant operating 330 d y^{-1} and 24 h d^{-1} could provide as much as 36.3 Mg h^{-1} of CO$_2$ gas to the torrefaction plant or for other uses. The "base case" life-cycle GHG emissions inventory data for corn ethanol were obtained from Kaliyan et al. [11] (Table 3).

The 0.38 hm^3 y^{-1} of corn ethanol (denatured) plant consumes 69 MW of natural gas to produce process steam (55.8 MW of steam), and 51.4 MW of natural gas for the co-products dryer [22–24]. The GHG emissions for the use of natural gas for producing process steam and for co-products dryer are 16.0 and 12.0 g MJ^{-1} of denatured ethanol, respectively (Table 3). Typical co-product dryers are direct-fired by natural gas, so they don't use process steam. Thus, when the torrefaction plant is co-located with the ethanol plant, steam

Table 3 – Effect of using process steam from a co-located corn stover torrefaction plant on the life-cycle greenhouse gas (GHG) emissions (carbon dioxide equivalents) for corn ethanol produced at a U.S. Midwest dry-grind corn ethanol plant.

GHG emission category	GHG emission (g MJ^{-1} of denatured ethanol)		
	Base case with natural gas fuel [11]	42.8% Process steam energy from torrefaction plant	100% Process steam energy from torrefaction plant
Input			
Corn production	36.2	36.2	36.2
Corn transportation	2.05	2.05	2.05
Natural gas for process steam	16.0	9.17[a]	0.00
Torrefaction off-gas volatiles for process steam	NA	1.38[b]	3.23[c]
Natural gas for co-product (DDGS) dryer	12.0	12.0	12.0
Electricity import from grid	8.33	8.33	8.33
Denaturant contribution	2.80	2.80	2.80
Depreciable capital	0.45	0.45	0.45
Ethanol transport to blend/sell	1.40	1.40	1.40
Output			
Ethanol (anhydrous) combustion	1.0	1.0	1.0
Co-product (DDGS) feed credit	−19.4	−19.4	−19.4
Net (i.e., input + output)			
Life-cycle net GHG emissions for ethanol (g MJ^{-1})	60.9	55.4	48.1
GHG reduction relative to gasoline (%)[d]	34.1%	40.0%	47.9%

Note: DDGS = dried distillers grains with solubles; NA = not applicable.

[a] Life-cycle GHG emission from the natural gas use for process steam = 16.04 × (1–0.4283) = 9.17 g MJ^{-1} carbon dioxide equivalent of denatured ethanol.

[b] Life-cycle GHG emission due to the use of torrefaction off-gas volatiles for process steam = (28.12 MW of volatiles × 3600 s h^{-1} × 14.04 g MJ^{-1} carbon dioxide equivalent of volatiles)/(47,777 dm^3 h^{-1} of denatured ethanol × 21.5 MJ dm^{-3} of denatured ethanol).

[c] A 317,693 Mg y^{-1} of biocoal (1.1% wet basis moisture content) producing torrefaction plant generates 65.65 MW of excess heat in the torrefaction off-gas volatiles, which can meet 100% of the process steam needs of the 0.38 hm^3 y^{-1} of corn ethanol (denatured) plant.

[d] The life-cycle GHG emission of gasoline is 92.3 g MJ^{-1} carbon dioxide equivalent of gasoline [10].

from the torrefaction plant is used to meet only the process steam demand of 55.8 MW (i.e., 4.2 MJ dm^{-3} of denatured ethanol). Depending on the amount of process steam available from the torrefaction plant, the amount of natural gas used for the process steam production is adjusted. Then, the reduction in the GHG emissions for corn ethanol due to the reduced use of natural gas at the ethanol plant is estimated.

By combusting the excess torrefaction off-gas volatiles (28.1 MW), steam is produced in a heat recovery steam generator (HRSG) at the torrefaction plant, and then the steam is piped to the ethanol plant. The efficiency of HRSG is assumed to be 85%. The practice of piping steam from one plant to another is currently employed in industrial settings. The GHG emissions associated with the steam piping process are assumed to be negligible.

2.2.4. *Coal-fired power plant*

The life-cycle GHG emission for electricity generated from a coal-fired power plant is derived from GREET [10]. The coal feedstock upstream emission (i.e., coal mining and cleaning, non-combustible emissions from coal mining and cleaning, and coal transportation to power plant) is 18.4 g kWh^{-1} carbon dioxide equivalent [10]. The GHG emissions due to coal fuel combustion and power plant infrastructure construction emissions are 371.1 and 0.204 g kWh^{-1} carbon dioxide equivalent, respectively [10]. Power plant generation efficiency is assumed to be 32.8% (equivalent to a net heat rate of 10,984 kJ kWh^{-1}). Electric transmission and distribution loss is considered to be 8% [10]. Thus, the life-cycle GHG emission for electricity generated from 100% coal is 1292.2 g kWh^{-1} carbon dioxide equivalent (at user wall outlet).

For co-firing biocoal with coal, biocoal is transported from the torrefaction plant as 22.7 Mg truck loads to a coal-fired power plant located at 321.9 km round-trip distance. The diesel consumption for truck is assumed to be 0.018 dm^3 Mg^{-1} km^{-1} with diesel heating value of 35.9 MJ dm^{-3} [13]. The life-cycle GHG emission (including production, transport, and combustion) for diesel is assumed to be 91.6 g MJ^{-1} carbon dioxide equivalent of diesel [10]. Thus, the GHG emission for diesel fuel use during truck transport is 0.90 g MJ^{-1} carbon dioxide equivalent of biocoal dry matter. The electrical energy required for pulverizing biocoal is assumed to be 10 kWh Mg^{-1} of biocoal at 1.1% w.b. moisture content [25–27], which is equivalent to emitting 0.45 g MJ^{-1} carbon dioxide equivalent of biocoal dry matter, applying the grid electricity GHG emission factor of 910 g kWh^{-1} carbon dioxide equivalent [11,12]. Combustion of corn stover in industrial boilers emits 0.0036 g of CH_4 MJ^{-1} of dry matter and 0.0102 g of N_2O MJ^{-1} of dry matter [10,13]. Therefore, the combustion emissions for corn stover biocoal (contribution from CH_4 and N_2O emissions, but excluding CO_2 emission) equal 3.13 g MJ^{-1} carbon dioxide equivalent of biocoal dry matter.

2.3. *Impact assessment and interpretation*

The life-cycle impact category considered for this study is global warming potential (GWP) for the emissions contributed by the three greenhouse gases (CO_2, CH_4, and N_2O). The three greenhouse gases are aggregated on a carbon dioxide equivalent basis using the 100-year horizon global warming potential (GWP) factors of 1 for CO_2, 25 for CH_4 and 298 for N_2O as recommended by the Intergovernmental Panel on Climate Change [28]. The life-cycle GHG emission for corn ethanol is compared to that of gasoline. The life-cycle GHG emission for co-fired electricity generated with co-firing 10%, 20%, and 30% (energy basis) of biocoal with coal is compared to that of 100% coal-fired electricity. All life-cycle GHG emission calculations were performed using Microsoft Excel® spreadsheet software.

3. Results and discussion

3.1. *Torrefaction plant*

The GHG emission for producing torrefaction volatiles (i.e., torrefaction process contribution) is 7.42 g MJ^{-1} carbon dioxide equivalent of volatiles (dry basis) (Table 2). Including corn stover logistics emissions of 6.61 g MJ^{-1} carbon dioxide equivalent of corn stover dry matter (Table 1), the life-cycle GHG emission for torrefaction off-gas volatiles is 14.04 g MJ^{-1} carbon dioxide equivalent of volatiles (at the torrefaction plant gate). For comparison, the life-cycle GHG emission for natural gas is 66.3 g MJ^{-1} carbon dioxide equivalent of natural gas, which includes emissions from upstream (i.e., production and distribution) and combustion in industrial boilers [10]. This suggests that replacing natural gas with torrefaction off-gas volatiles for heat/power production could reduce GHG emissions for existing natural gas users such as corn ethanol plants and district heating facilities.

The GHG emission for producing biocoal (i.e., torrefaction process contribution) is 4.74 g MJ^{-1} carbon dioxide equivalent of biocoal dry matter (Table 2). Including corn stover logistics emission, the life-cycle GHG emission for producing biocoal (at the torrefaction plant gate) is 11.35 g MJ^{-1} carbon dioxide equivalent of biocoal dry matter or 229.5 kg Mg^{-1} carbon dioxide equivalent of biocoal at 1.1% w.b. moisture content. Biocoal may have a market as a GHG reducing coal substitute in coal-fired power plants or may be a feedstock for further pyrolysis or gasification for combined heat and power or Fischer-Tropsch liquids [1,3,29].

We estimate that the torrefaction plant processing 30.3 Mg h^{-1} of corn stover at 17% w.b. moisture content consumes 2.5 MW of electricity (Table 2). Bergman et al. [4] reported electrical energy consumption of 2.6–3.0 MW for a torrefaction plant processing 64.6 Mg h^{-1} of wood chips at 50% w.b. moisture content. This range of electrical energy input was derived for a torrefaction plant with an indirectly-heated screw reactor (2.55 MW), a directly-heated rotary drum reactor (3.0 MW), or a directly-heated-moving bed reactor (2.61 MW) [4].

3.2. *Corn ethanol plant*

The results show that the excess heat energy (28.1 MW) from a 136,078 Mg y^{-1} of biocoal (1.1% w.b. moisture content) producing torrefaction plant can meet 42.8% of the process steam needs (excluding the co-products dryer heat demand) of the 0.38 hm^3 y^{-1} of corn ethanol (denatured) plant (i.e., 1.80 MJ dm^{-3} of denatured ethanol). This results in a life-cycle GHG emission reduction of 40.0% for corn ethanol compared to gasoline (Table 3). For comparison, the “base case" corn ethanol plant using natural gas for producing process steam results in life-cycle GHG emissions reduction of 34.1% for corn ethanol compared to gasoline (Table 3). Scaling up, a 317,693 Mg y^{-1} of biocoal (1.1% w.b. moisture content) producing torrefaction plant can meet 100% of the process steam needs (excluding the co-products dryer heat demand) for a 0.38 hm^3 y^{-1} of corn ethanol (denatured) plant (i.e., 4.20 MJ dm^{-3} of denatured ethanol). Meeting 100% process steam needs could result in 47.9% GHG emission reduction for corn ethanol compared to gasoline (Table 3). Thus, co-location and integration of the torrefaction plant with an ethanol plant has substantial potential to reduce the carbon footprint of corn ethanol. A lower carbon footprint corn ethanol may qualify for GHG reduction incentives such as Class 5 RINs [Renewable Identification Number(s)], an upcoming standard proposed by the U.S. Environmental Protection Agency (EPA) [30].

3.3. *Coal-fired power plant*

The life-cycle GHG emission for electricity produced with 100% biocoal is 187.6 g kWh^{-1} carbon dioxide equivalent (at user wall outlet) (Table 4). In contrast, the GHG emission for electricity produced with 100% coal is 1292.2 g kWh^{-1} carbon dioxide equivalent (at user wall outlet) [10]. The upstream emission for 100% biocoal electricity (logistics, torrefaction, and biocoal truck transport emissions) is 43.6 g kWh^{-1} carbon dioxide equivalent; however, for 100% coal electricity, the upstream emission is 18.4 g kWh^{-1} carbon dioxide equivalent [10]. GHG emission from the power plant for 100% biocoal electricity (pulverizing, combustion, and infrastructure construction emissions) is 13.0 g kWh^{-1} carbon dioxide equivalent; while for 100% coal electricity, it is 371.3 g kWh^{-1} carbon dioxide equivalent [10]. Although 100% biocoal electricity emits 2.4 times higher upstream emissions than for the 100% coal electricity, 100% biocoal electricity emits 28.6 times lower power plant emissions compared to 100% coal electricity.

Co-firing 10%, 20%, and 30% (energy basis) of biocoal reduces GHG emissions of coal generated electricity by 8.5%, 17.1%, and 25.6%, respectively (Table 5). Electricity generated with 100% biocoal would result in 85.5% lower life-cycle GHG emissions than for 100% coal generated electricity (Table 5). In addition to the GHG reduction benefits, use of biocoal rather than raw biomass may offer several additional benefits. It has been argued that biocoal is a much better drop-in fuel for co-firing with coal than untreated biomass because biocoal can be ground to a particle size similar to that of pulverized coal, with lower energy use than for unprocessed biomass [4,5,27]. Biocoal is hydrophobic, which keeps it from absorbing moisture and permits transportation in open railcars and stockpiling at outdoor storage sites [3–7]. The co-firing percentages of raw biomass are often limited to 20% (energy basis) because the physical and chemical properties of raw biomass are much different than coal [31,32]; however, biocoal may allow much higher co-firing percentages (>20% energy basis) because biocoal properties are compatible with those of coal. Moreover, use of biocoal rather than raw biomass may result in lower additional capital investment, lower feedstock transport cost, lower feedstock storage loss, and higher GHG reduction incentives [33,34].

Table 4 – Life-cycle greenhouse gas (GHG) emissions (carbon dioxide equivalents) inventory for electricity production from 100% biocoal.

Emission source	GHG emission	
	g MJ^{-1} of biocoal dry matter	g kWh^{-1}
Upstream emissions		
Corn stover supply logistics	6.61	23.55[a]
Torrefaction process contribution	4.74	16.86[a]
Truck transport of biocoal to power plant	0.90	3.22[a]
Total upstream emission (A)	12.25	43.62
Power plant emissions		
Pulverizing biocoal at power plant	0.45	1.60[a]
Combustion of biocoal	3.13	11.14[a]
Power plant infrastructure construction	0.06[b]	0.20[a]
Total power plant emission (B)	3.64	12.95
Life-cycle GHG emissions		
Electricity from 100% biocoal (at power plant gate), [(A + B)/0.328]	–	172.61[c]
Electricity from 100% biocoal (at user wall outlet)	–	187.62[d]

[a] GHG emission, g kWh^{-1} = data on g MJ^{-1} of biocoal dry matter × 3.6 × 0.989. Moisture content of biocoal is 1.1% (wet basis). Conversion, 1 kWh = 3.6 MJ.

[b] GHG emission for power plant infrastructure construction [10] = [0.204 g kWh^{-1}/(3.6 × 0.989)] = 0.06 g MJ^{-1} of biocoal dry matter. Moisture content of biocoal is 1.1% (wet basis). Conversion, 1 kWh = 3.6 MJ.

[c] It is assumed that the power plant generation efficiency is 32.8%.

[d] It is assumed that the electric transmission and distribution loss is 8%. Life-cycle GHG emission at user wall outlet = Life-cycle GHG emission at power plant gate/0.92.

Because generation of electricity is the largest single source of GHG emissions in the U.S. and much of the world, biocoal could add immense value to coal-fired power generators as they attempt to meet policy goals for GHG reductions and pay fees and/or taxes on GHG emissions. Because biocoal can be blended and used in existing coal-fired power plants, biocoal can gradually replace a portion of the coal currently being used and thus reduce GHG emissions. If gradually increased in a blend with coal, biocoal may be able to extend the economic lives of existing coal-fired power plants.

3.4. *Torrefaction plant with CHP system*

A sensitivity analysis was conducted to include a combined heat and power (CHP) system at the torrefaction plant where a back-pressure steam turbine produces electricity. Steam is produced using the excess heat from the torrefaction off-gas volatiles (28.1 MW) at a heat recovery steam generator (HRSG) efficiency of 85%. The turbine produces 2.5 MW of electricity at 10.3% efficiency, which meets 100% electricity demand by the

Table 5 – Life-cycle greenhouse gas (GHG) emissions (carbon dioxide equivalents) for biocoal co-fired electricity.

Biocoal co-firing percentage (energy basis)	Life-cycle GHG emission for electricity (at user wall outlet) (g kWh^{-1})	GHG reduction for co-fired electricity compared to coal-fired electricity (%)
0%	1292.2	0%
10%	1181.7[a]	8.5%
20%	1071.2	17.1%
30%	960.8	25.6%
100%	187.6	85.5%

[a] For this case, the GHG emission for electricity is calculated as: $(0.90 \times 1292.2) + (0.10 \times 187.6) = 1181.7$ g kWh^{-1}.

torrefaction facility. The assumed power generation efficiency of 10.3% is within the range of biomass CHP system power generation efficiencies reported in the literature [35].

The steam exiting the turbine (21.5 MW) is sent to the co-located corn ethanol plant to meet process steam needs and the condensate is returned to the CHP system at the torrefaction plant. The turbine outlet steam energy meets about 38.4% of the process steam needs (excluding the co-products dryer heat demand) of the 0.38 hm^3 y^{-1} of corn ethanol (denatured) plant (i.e., 1.62 MJ dm^{-3} of denatured ethanol). Since waste energy from the turbine steam is sent to the ethanol plant, no GHG emission is associated with this steam energy. For this scenario, GHG emission reduction for corn ethanol compared to gasoline is 40.7%; while for the case with no CHP system at the torrefaction plant, the GHG emission reduction is 40.0% for corn ethanol compared to gasoline. Scaling up, a 354,010 Mg y^{-1} of biocoal (1.1% w.b. moisture content) producing torrefaction plant can meet 100% of the process steam needs (excluding the co-products dryer heat demand) for a 0.38 hm^3 y^{-1} of corn ethanol (denatured) plant (i.e., 4.20 MJ dm^{-3} of denatured ethanol). Meeting 100% process steam needs could result in 51.4% GHG emission reduction for corn ethanol compared to gasoline.

The GHG emission for producing biocoal (i.e., torrefaction process contribution) is 0.313 g MJ^{-1} carbon dioxide equivalent of biocoal dry matter. In this case, the only GHG emission source is the natural gas used for the combustion of torrefaction off-gas volatiles. Including corn stover logistics emission (6.61 g MJ^{-1} carbon dioxide equivalent of stover dry matter), the life-cycle GHG emission for producing biocoal (at the torrefaction plant gate) is 6.93 g MJ^{-1} carbon dioxide equivalent of biocoal dry matter or 140.1 kg Mg^{-1} carbon dioxide equivalent of biocoal at 1.1% w.b. moisture content. This corresponds to about 39% reduction in GHG emission for the biocoal compared to the case where torrefaction plant purchases electricity from the grid (i.e., 229.5 kg Mg^{-1} carbon dioxide equivalent of biocoal at 1.1% w.b. moisture content).

The life-cycle GHG emission for electricity produced with 100% biocoal is 135.4 g kWh^{-1} carbon dioxide equivalent (at user wall outlet), which is about 28% lower emission than the case where the torrefaction plant purchases grid electricity (i.e., 187.6 g kWh^{-1} carbon dioxide equivalent). Co-firing 10%, 20%, and 30% (energy basis) of biocoal reduces GHG emission of coal generated electricity by 9.0%, 17.9%, and 26.9%, respectively. Future work is required to determine if the GHG reduction benefits would surpass the additional cost of the CHP system.

4. Conclusions

The following conclusions were drawn from this study.

- For a stand-alone corn stover torrefaction plant processing 30.3 Mg h^{-1} of corn stover at 17% wet basis (w.b.) moisture content, the life-cycle greenhouse gas (GHG) emission (at the torrefaction plant gate) for the production of biocoal (including corn stover logistics GHG emissions) is 229.5 kg Mg^{-1} carbon dioxide equivalent of biocoal at 1.1% w.b. moisture content (i.e., 11.35 g MJ^{-1} carbon dioxide equivalent on a dry mass basis).
- Co-locating and integrating a corn stover torrefaction plant with a natural gas-fueled dry-grind corn ethanol plant and sending the steam produced from the excess heat from the torrefaction off-gas volatiles at the torrefaction plant to meet the process steam needs of the corn ethanol plant could lower the carbon footprint of corn ethanol.
- Co-firing 10%, 20%, and 30% (energy basis) of corn stover biocoal at a coal-fired power plant reduced the life-cycle GHG emissions of electricity generated by 8.5%, 17.0%, and 25.6%, respectively, compared to 100% coal-fired electricity.
- A combined heat and power (CHP) system installed at the torrefaction plant to meet 100% electricity demand of the torrefaction plant would result in lower GHG emissions for biocoal, corn ethanol, and co-fired electricity than for the case where the torrefaction plant purchased electricity from the grid.

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